

# Color Contrast Theory as a Path to Improved Visualization of Scientific Data

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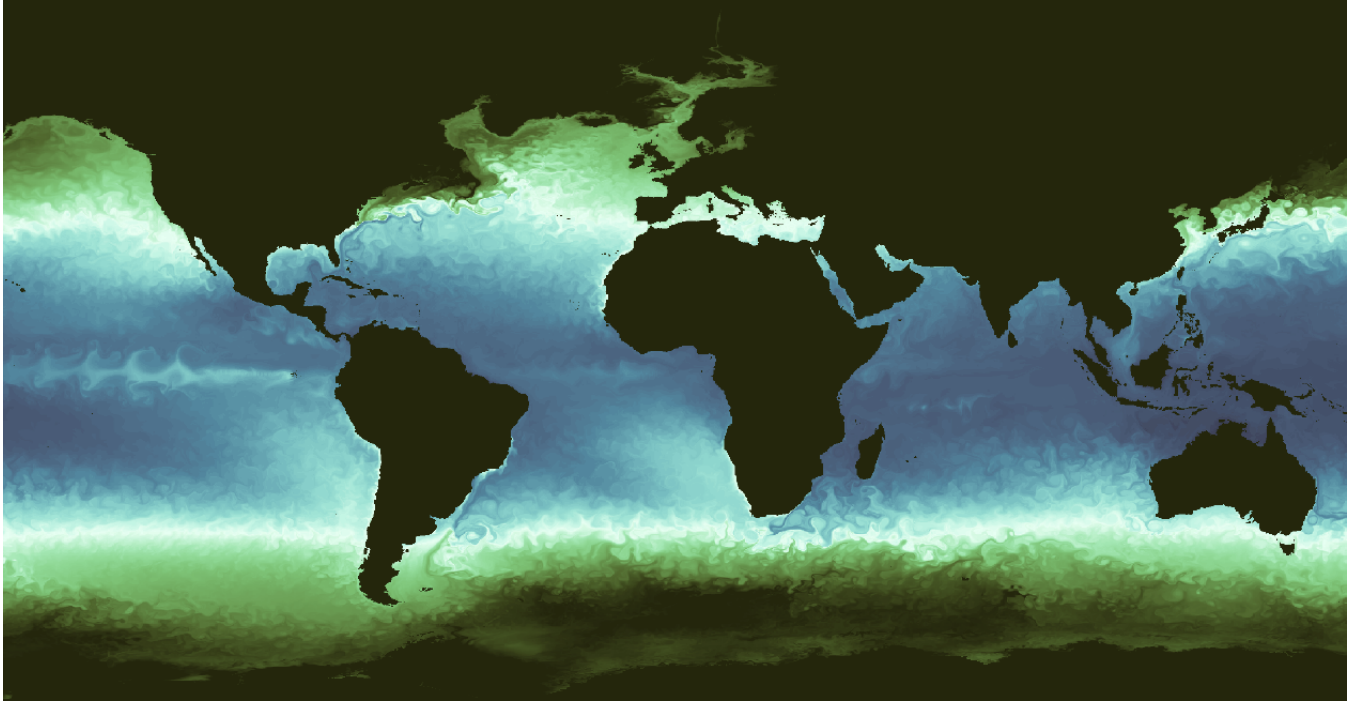


Figure 1: Results from a climate simulation computed using the Model for Prediction Across Scales (MPAS) code [9]. This visualization shows the temperature of ocean currents, using a green and blue color scale. These colors were specifically selected because of the large range of colors that we can perceive in this color space. As discussed in this paper, an artist has applied Itten’s theories of color contrast through a color scale, creating a smoothly varying color range designed to increase the amount of detail that can be perceived within the data.

## ABSTRACT

A critical component in rendering scientific data is mapping colors to scalar variables. Much of the work in this area has been motivated by perceptual principles, leading to calls for better color scales than the often used rainbow scale [3]. Approaches to designing color scales tend to be motivated by principles of perception and digital color spaces, and this has had a broad and positive impact on how we look at data. To extend this impact, our team is motivated from historical principles of artistic color theory, and draws upon expertise across several disciplines to achieve color scales that are

grounded in color theory, are computable, and which strive for maximum clarity within a constrained color space. In particular, our color scales simultaneously manipulate hue, saturation and value, and incorporate other principles of color theory, to create highly perceptible contrast in our data visualizations.

**Index Terms:** I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture;

## 1 INTRODUCTION

An artist uses color to direct attention, differentiate subjects and organize the visual flow in a painting. A scientist may have these same aims in mind when creating a visualization of complex scientific data. Our contribution is combining these to explore the application of an artist’s expertise in color to achieve better visualization of scientific data.

We begin by noting that when we apply the concepts detailed in this paper to a color scale, we achieve perceptible differences in the display of information. Figure 2 demonstrates the impact of

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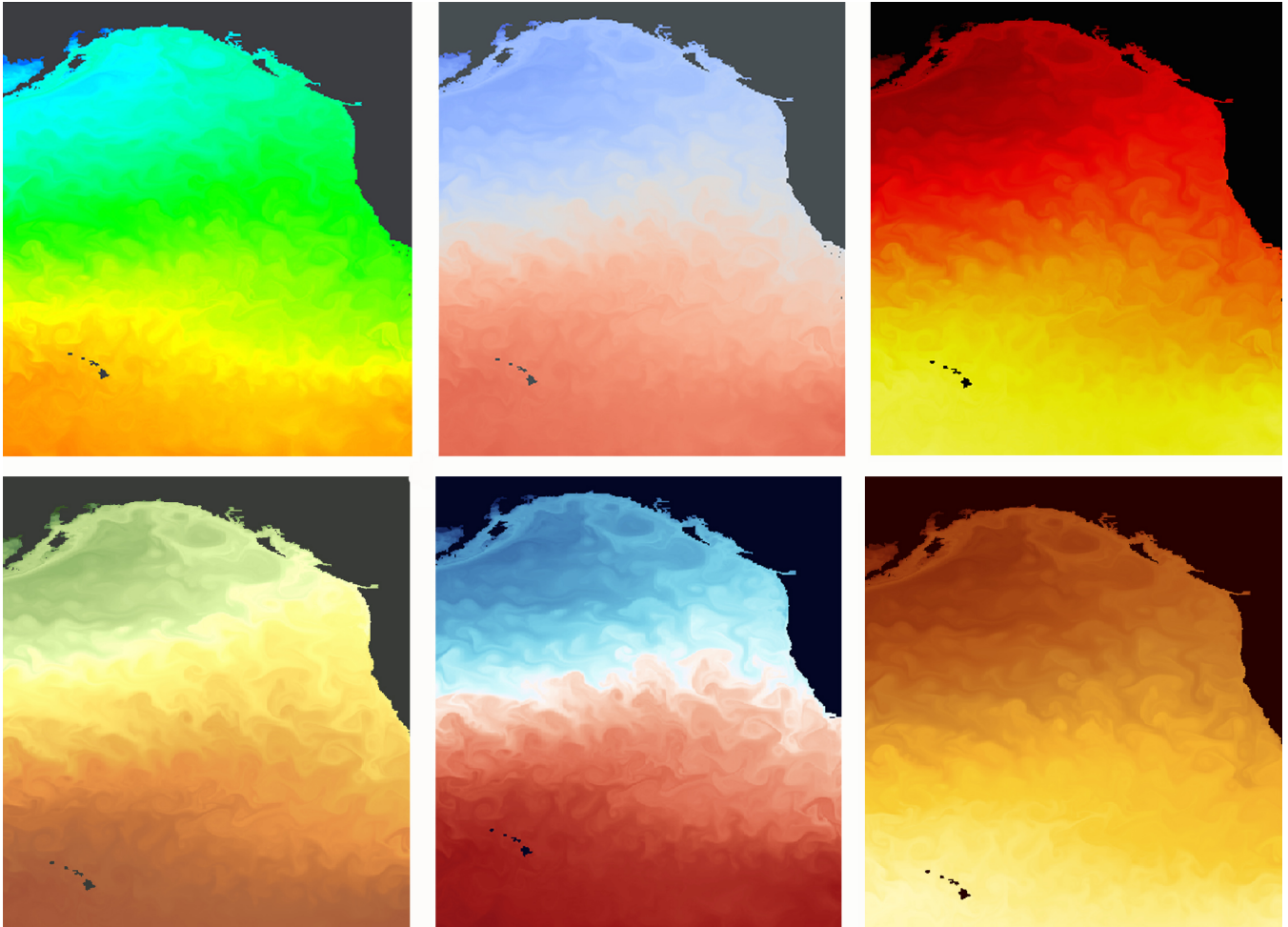


Figure 2: Composite figure showing ocean temperature data in six different color scales. At the top are commonly used standard color scales Rainbow, Warm-Cool and Heat Map. Below are alternatives which employ four principles of color contrast: (1) contrast of hue (an expanded range of hue in this case), (2) contrast of saturation, and (3) contrast of value; as well as (4) warm/cool contrast within the blues and greens themselves. Using these principles creates a more perceptually detailed rendition of the data.

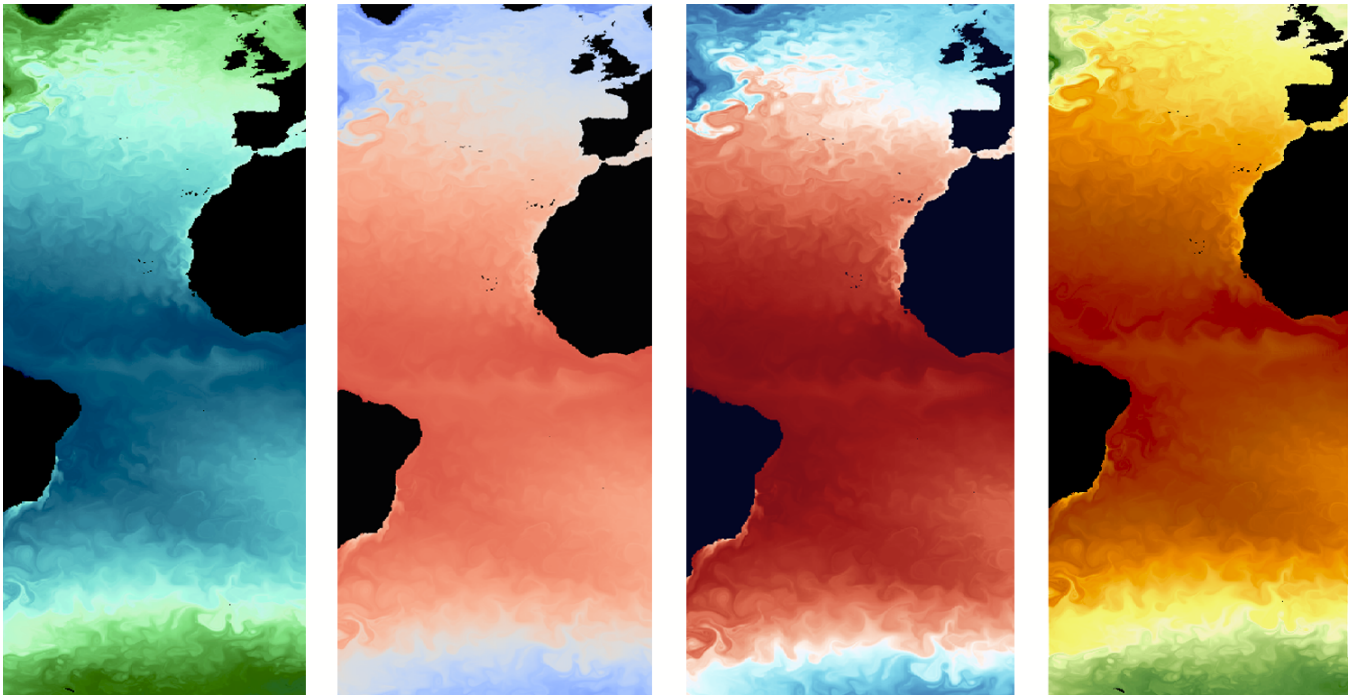


Figure 3: Images showing the Atlantic Ocean, between South America and Africa, of a Model for Prediction Across Scales (MPAS) code simulation [9]. The color scales used, from left to right, are contrast-enhanced green/blue, standard red/blue, contrast-enhanced red/blue, and contrast-enhanced amber/green. Note in particular the increase in detail achieved over a widely used standard red/blue colormap when contrast is applied. In addition, we note an increase in detail shown in all contrast-enhanced color scales, when compared to the standard red/blue. Color contrast theory as applied in this paper promotes this increase of detail in harmoniously colored images using a constrained range of colors.

perception and color contrast theories applied to a scientific visualization of ocean temperature data. The figure shows simulation results from the Model for Prediction Across Scales (MPAS) [9] code, colored with three different color scales. At the bottom is a divergent warm/cool color scale which moves from blue (low) to red (high). In the middle is the widely used rainbow color scale. At the top is an example of a color scale that employs four principles of color contrast: (1) contrast of hue (an expanded range of hue in this case), (2) contrast of saturation, and (3) contrast of value; as well as (4) warm/cool contrast within the blues and greens themselves. Note the increase in sharpness in the top images, in comparison to the other two. This is due to the increased contrast achieved in both the blue and green spectra. Note also that though there are only two hues used in the top color scale, there are clearly distinguishable features that are not visible in the other two.

A good visualization should be easy to understand, uncluttered, and coherent. Research shows that colors can often obscure information, and it is often useful to determine specific tasks that may be aided by the use of color [12]. Systems have been developed to assist color scale selection through sets of rules that take into account characteristics of the data and the task [2] [13]. Color choice in visualization has been a topic of research for decades, and much progress has been made in codifying rules for color use [2], methods for choosing optimal color scales [5, 10] and understanding how different color spaces impact digital visualizations [8, 14]. Much of the work emphasizes the importance of principles of perception [3], characteristics of the data [2] [14], the necessity of allocating attention [15] and the importance that the specific task has in the choice of colors [2].

Ware states that useful color scales should spiral up through HSV space [14]. Research has shown that choosing colors is important. However, it is also difficult. In a similar domain, web designers

have many tools available to choose color sets that help define the look and the clarity of web pages. However, there are few similar tools for scientists. For those inexperienced in color theory, choosing color is usually a matter of using preset color scales. We embrace the fact that color choice is difficult, and believe we should call on an expert in color to help us with this.

We believe that a missing element in this research has been the incorporation of artistic color theory - as applied by experts in the theory - to help maximize the efficacy of color scales. By applying the fundamental principals of color theory to scientific visualization color scales, our work can increase perception of data, while at the same time minimizing the range of color needed. Importantly, these color scales can increase perception of data while at the same time minimizing color interactions that can negatively impact visualization of data.

We note that in much previous work, a challenge of color scales is to promote understanding of both image (2D) and three dimensional (3D) data. This paper concentrates on a use case for image data, but the principles of contrast and color are known to apply to the 3D cases as well [14, 8, 11]

In this paper, we present theoretic and applied approach to color scale design that can lead to highly coherent, perceptually-optimized visualizations. Importantly, we discuss how experts from a number of fields collaborate to create color scales that increase color contrast and coherence that can be used in existing tools. We discuss the positive and negative impacts color contrast can have on the equalized representation of data in an effort to minimize perceptual distortions in the data and achieve color harmony that equalizes attention to all areas of the data.

## 2 ITTEN'S SEVEN TYPES OF CONTRAST

Modern color theory has been built on the work of both scientists and artists across several centuries.

Until the 16<sup>th</sup> century, artists were hampered by the limitations in their pigments and materials. Then the Flemish painter Jan van Eyck became one of the first prominent artists to master the use of oil as a medium. This enabled the rich realistic renderings we associate with the Renaissance. In 1704, Sir Isaac Newton published his *Opticks*, detailing results from his experiments with light and prisms. In this work, he codified the color circle, or color wheel - a construct still in use today. In 1810, the writer and philosopher Goethe published *The Theory of Colors*, which contributed a focus on how humans perceive color, rather than the physics of the optical spectrum. Around the 1900's, Van Gogh and the artists of the Fauvism Movement (including Matisse) became known for their mastery of and exploration of color. These artists laid the foundation for the color studies and theories of Josef Albers and Johannes Itten, whose work is the basis for color theory today.

In 1961, Johannes Itten codified a system of contrasts of color in his work *The Art of Color: The Subjective Experience and Objective Rationale of Color*. Interestingly, Itten's title demonstrates the dynamic nature of our perception of color, which has both objective and subjective dimensions.

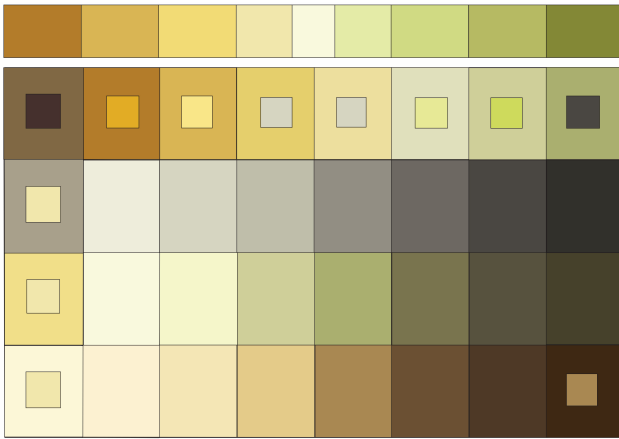


Figure 4: This grid depicts a value range of a neutral, cool and warm hues - a warm gray, muted green, and muted orange. This is a powerful contrast, though it is achieved with muted colors.

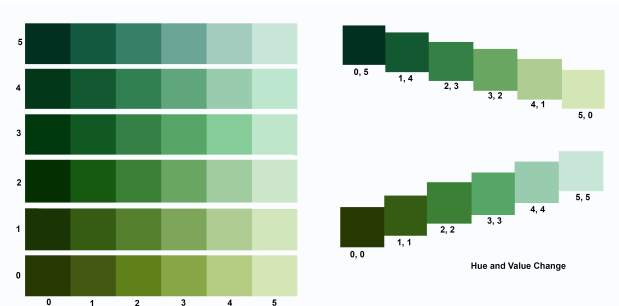


Figure 5: This grid illustrates the cool to warm range within green. The contrast impacts all hues, but is most evident in green because it contains the widest perceivable range of hues. In the top row are cool greens. Moving down the rows, the greens move toward warm tones. Diagonals of this grid show the colors that move through value and warm-colored contrast.

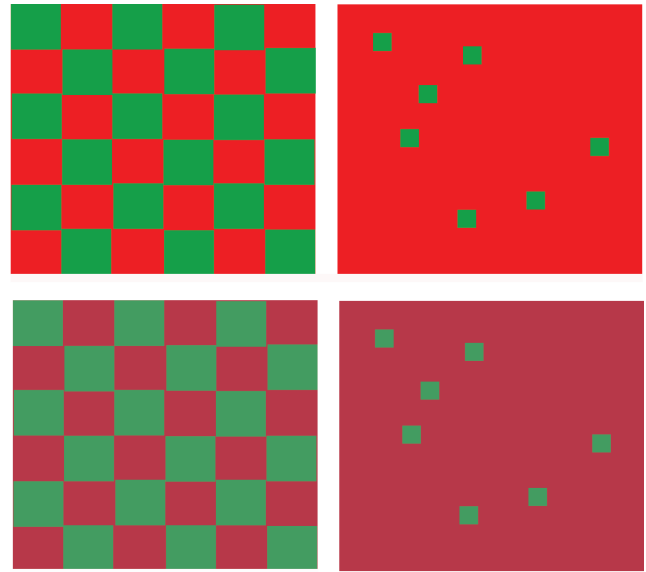


Figure 6: These images show the principles of simultaneity and extension contrast. Simultaneity of color causes vibration between saturated color complements as can be seen in the top left square. Contrast of extension causes a misperception of the area ratio between colors, as is seen on the top right. Both of these issues are mitigated by muting the colors, as is seen in the bottom two squares.

Itten's color contrasts are important qualities of color theory that allow us to create perceptually differentiated color scales [7, 6], and are the formal organizing principles for the color scale designs in this paper.

The seven principles of contrast from Itten's *Art of Color* are:

1. **The Contrast of Hue.** Hue is chroma, and is the part of color that we typically name ('red', 'blue', 'violet', etc.). It refers to a specific place on the color wheel.
2. **Light-dark Contrast.** This is also known as 'value', and is the range from dark to light within a color.
3. **Cold-warm Contrast.** Cold and warm refer to families of colors. Cool colors are in the blue, green and purple family. Warm colors are in the yellow, orange and red family. This is a powerful contrast, and lets us work with a muted palette as we see in Figure 5.
4. **Complementary Contrast.** Complementary colors are those on opposite sides of the color wheel: red/green, orange/blue and yellow/purple. When used in combination, they produce a naturally harmonious image.

There is one exception worth noting. When complementary colors are used in full saturation, they can produce significant distortions in our perception of data [15], due to Contrast of Extension (#7) and Simultaneous Contrast (#5). See Figure 6. It is often beneficial to use slightly muted complements.

5. **Simultaneous Contrast.** Also known as the Contrast of Simultaneity, this contrast refers to the interaction of colors and how our perception alters them. Colors adjacent to each other are perceived differently than the same colors in isolation. Our minds increase the perceptual contrast to get adjacent colors closer to their complement. The principle is most pronounced in saturated colors.



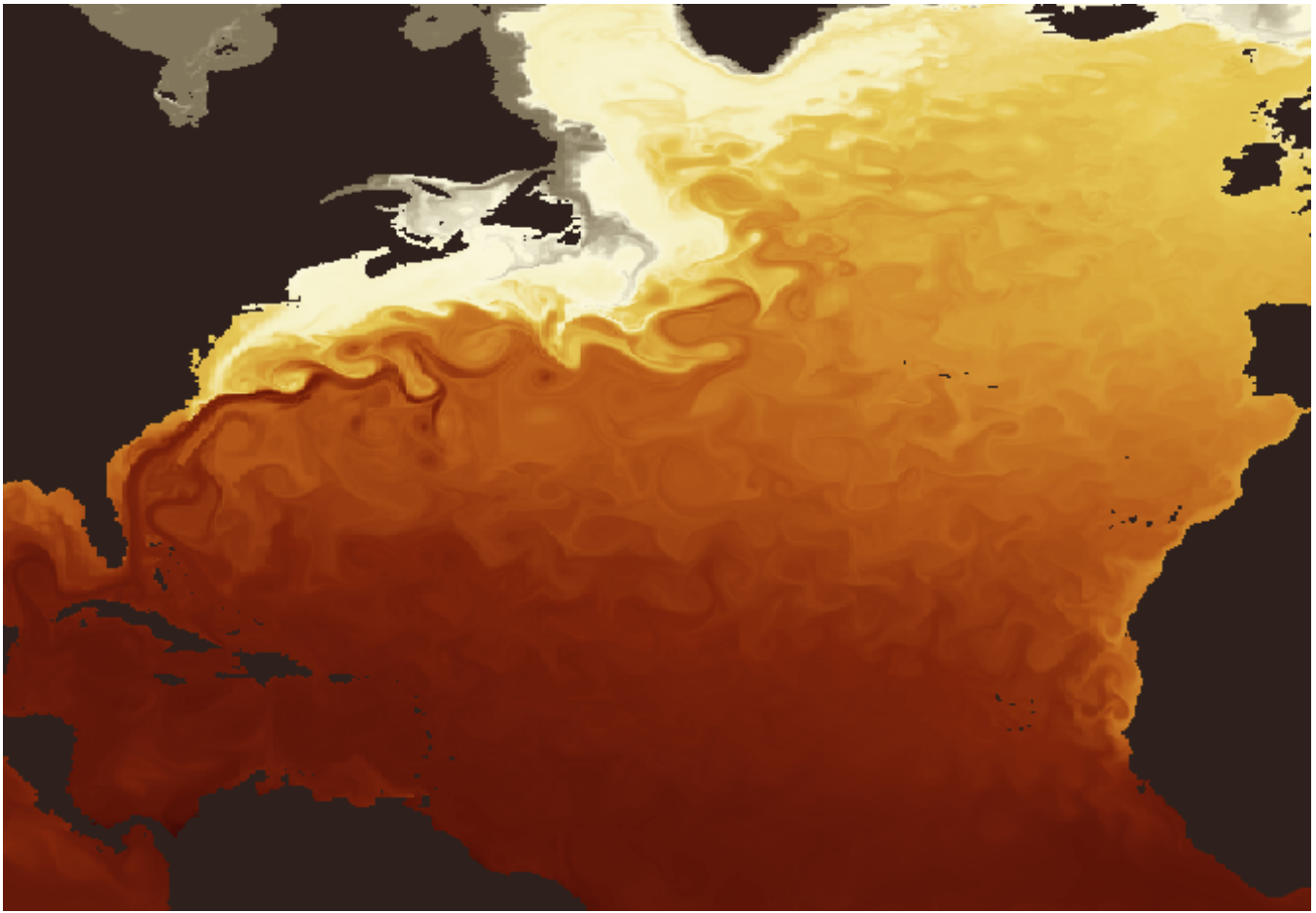


Figure 7: This image shows an important contribution of this work - a color scale showing a wide range of detail in scientific data while using a narrow range of the color spectrum. The color scale appears as a simple and continuous gradation of color, but it moves subtly through hue and saturation to achieve this effect. One is not immediately aware of this movement through hue and saturation. Because the artist has adjusted saturation and value in tandem with each other in order to maintain the continuity of color. Thus, we have found designed sets of saturation and value curves that produce the perception of continuity. Using a color scale which appears to move only through value has two advantages: 1) the narrow range of hue creates an uncluttered image upon which a wide range of variables can be mapped, and 2) it avoids the issues created by color simultaneity and an imbalance of color extension.

**6. The Contrast of Saturation.** Saturation refers to the intensity or purity of a color. A fully saturated color is not muted by another color, or by the addition of black or white.

**7. Contrast of Extension.** Also known as the Contrast of Proportion, this contrast refers to the area ratio of complementary colors in an image. It is controlled by balancing the size of areas of color, and the 'weights' of the colors. For example, orange is a very strong color, having more 'weight' than an equal area of its complement, blue.

### 3 TRADITIONAL COLOR THEORY APPLIED TO SCIENTIFIC VISUALIZATION

Perceptual research shows that an object that varies by two characteristics, rather than a single characteristic, is easier to distinguish within a field [15]. Commonly used scientific visualization color scales rely on one, and sometimes two, types of color contrast. For example, the rainbow color scale relies on hue contrast with constant saturation. The warm/cool color scale [8] is a divergent color scale that differentiates through value of the reds and blues. This is one of the main reasons that we vary more than one dimension of the color at the same time.

For greatest control when implementing the principles of color contrast, we work in HSV space, a color space in which Hue (H), Value (V) and Saturation (S) can be independently manipulated. This aligns well with the color theory principles of contrast, and enables us to create color scales based on multiple color contrasts, resulting in a higher degree of differentiation. We believe this will enable researchers to perceive more detailed information in their data. We have chosen to work in HSV space because it

The workflow for creating these color scales requires a large number of control or color points (typically around 20), to allow the smooth transitions between precisely controlled HSV values. In order to be useful to scientists using real tools, we need to ultimately produce color scales that can be useful in standard data analysis software. A first step in implementation was to develop a mathematical representation to address the large number of control points, and for this we partnered with a statistician. Together we identified functions, which corresponded to the HSV curves, generated by our new color scales.

Our design workflow started with a tool to create and interpolate points in HSV space, with which we created a series of perceptually equalized color scales. The HSV points were then graphed

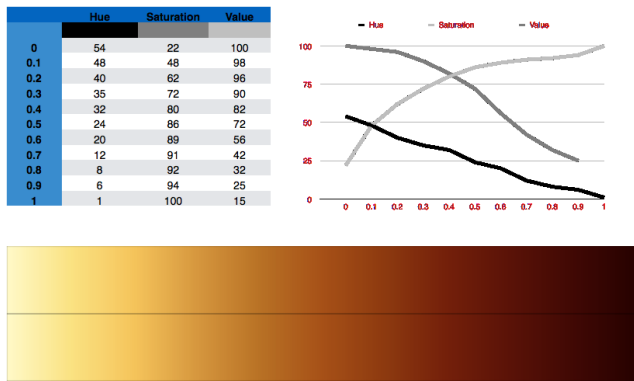


Figure 8: Images showing the workflow in developing HSV color scales with a high number of color points. The graph in the upper right plots the hue, saturation and value points (HSV) independently. By looking for similarities in the curves created by the artist, we found similarities in the saturation and value curves. Close-fitting functions were then found for these curves, allowing for a more streamlined implementation.

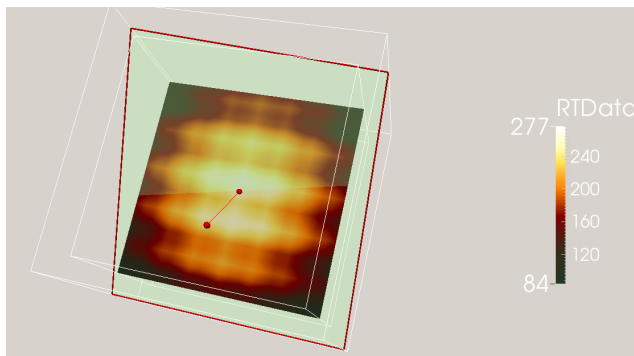


Figure 9: This image shows a visualization of primarily warm colors. Thus by creating a semi-transparent screen of a cool complement, we are able to desaturate sections of the visualization. Our attention is then focused on the unscreened sections. This technique could be applied with a range of transparencies to sort or focus attention on data.

to look for patterns within each of the variables. Figure 8 shows this workflow in practice for a color scale moving from amber to brown. The table shows a set of HSV values for a single color scale. In practice, we found that the HSV curves for many of the artists-developed color scales shared common properties - a fact that we hope to exploit to simplify the application of this work as our workflow matures.

### 3.1 Extending Hue Within a Common Divergent Colormap

A good way to begin our exploration of contrast is by considering how to improve a widely used divergent color scale used as the default in some common scientific visualization applications (Figure 3). This color scale was carefully design to be useful across a wide array of data types, and useful for both flat and three dimensional data [8]. This divergent color scale is a far better initial color scale to apply than the rainbow color scale, which it replaced as the default [3].

We applied several color contrasts to this color scale to help increase the visible detail, discrimination of color ordering, while maintaining uniformity in distinguishing values across the color

scale.

The warm/cool color scale is constricted by a narrow range of hue and saturation. It relies on the value steps within the blue and red selected. Figure 3 and Figure 7 demonstrates the expanded perceptible detail gained by incorporating a range of hue and saturation.

We can build harmonious visualizations through the use of warm/cool contrasts. When we think of warm/cool colors, we think of reds to yellows versus blues to greens. There are also warm and cool varieties of each color. For example, blue-green is a cool blue. Blue-purple is a warm blue. Contrast within colors is often useful in scientific visualization because it can be employed to create perceivable but not disruptive differences within the color scale.

### 3.2 Extending the Blue Spectrum

The widely used warm/cool color scale in Figure 3 uses a narrow hue range of blues, but blue is a powerful color that can be exploited on its own. Figure 10 is an example of the increased perceptual range that can be achieved by incorporating a wider range of hue. The top two pictures use blues in the turquoise range. Hues from 170 to 180 degrees on the hue spectrum are represented here. By expanding the blues into the royal blue hues - increasing the range of hue to 160 to 250 degrees - we see greater differentiation in the data. The greater level of perceptible detail between the coasts of South America and Africa is typical of an expanded hue range.

### 3.3 Manipulating Saturation Within the Green and Blue Spectra

Green hue is the widest spectrum available to the human eye. Moving through the full spectrum of greens and full levels of saturation provides a large range of perceptible colors. Figure 11 shows a visualization that takes advantage of saturation of color within a blue and green divergent color scale. Note the detail in both the blue and green areas of the visualization of the entire globe in the topmost figure. We achieve this result by interleaving saturated and unsaturated colors within the same hue. The bottom images show in detail the ranges of both greens and blues used to achieve this. The available range of greens spans two-thirds of the color scale. Maintaining an equivalent perceptible differentiation in the blue range spans the remaining third.

The standard rainbow color scale takes advantage of the full range of hues, but because they are represented in full saturation, the differentiation gained by hues is undermined by perceptual distortions caused by simultaneity. This is well understood, and is one reason that the community advocates using a different set of default color scales [3]. Under full saturation, simultaneity causes vibration and perceptual distortion of area ratios within an image, a phenomenon which can be seen in the upper right portion of Figure 6. Lowering the saturation alleviates both issues, as seen in the bottom images of the same figure.

### 3.4 Contrast of Complementary Colors and Contrast of Warm/Cool

Complementary colors reside on opposite sides of the color wheel. As Joseph Albers research shows in *The Interaction of Color* [1], the brain prefers to see a harmonious balance of warm/cool color. Because of this, complementary colors are a very powerful form of contrast, and we can use this to our advantage. Using complementary colors enables us to make color scales with a narrower range of saturation and value. The narrower range creates a more harmonious image while preserving the range of hues for other components needed in a multivariate dataset. See Figure 4 for an example of a muted, high contrast colors.

Another practical application for complementary color contrast takes advantage of the fact that complements mixed together, even digitally, to mute each other. Using a complementary color in a

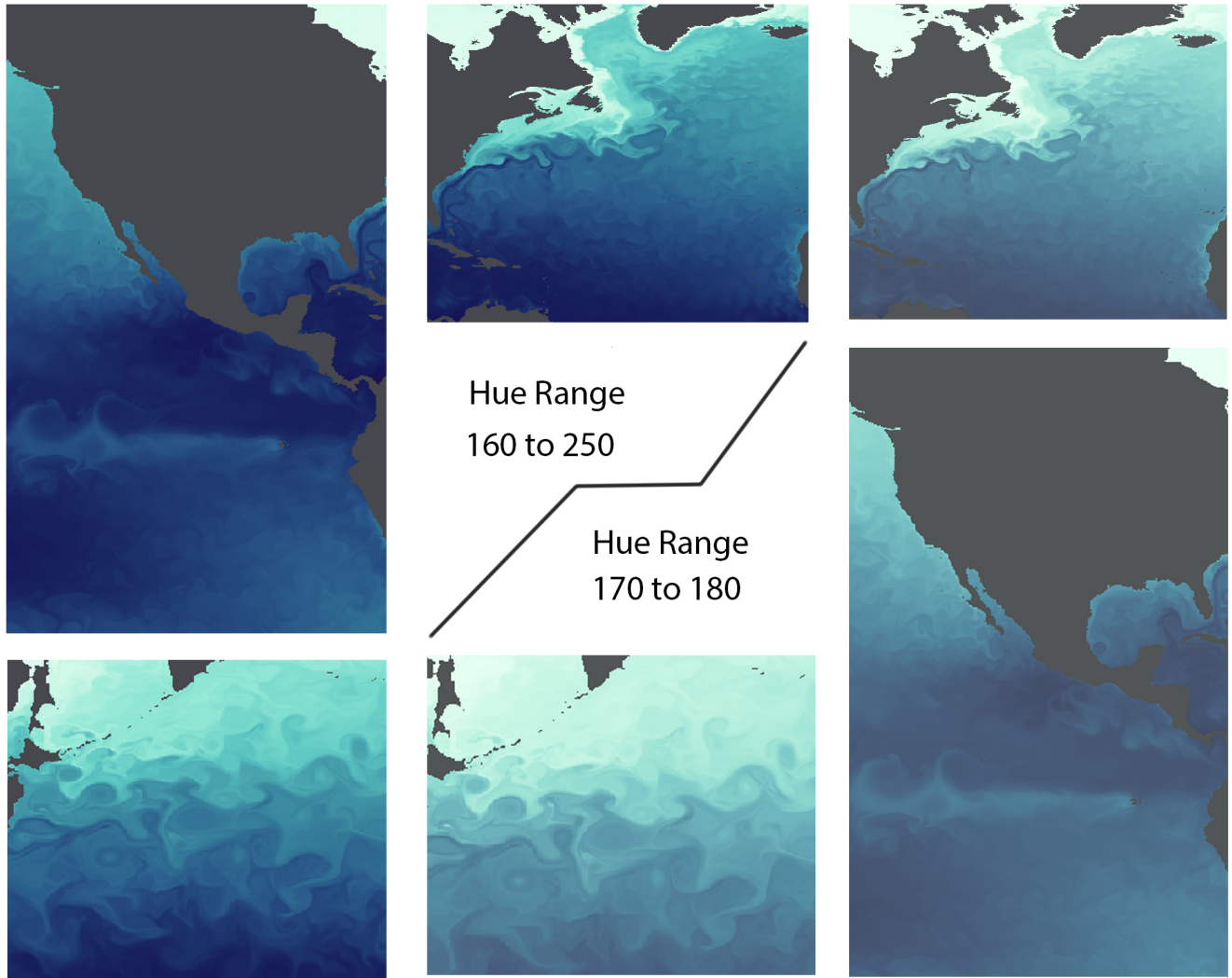


Figure 10: These images move through all three dimensions of HSV space: a narrow spectrum of Hue, a medium selection of Saturation and the full range of Value. The lower image is adjusted to incorporate the full range of blues, a wider spectrum of saturation and again the full range of value. By adding a wider range of hue and saturation we are able to expand the readily perceivable increments in the data.

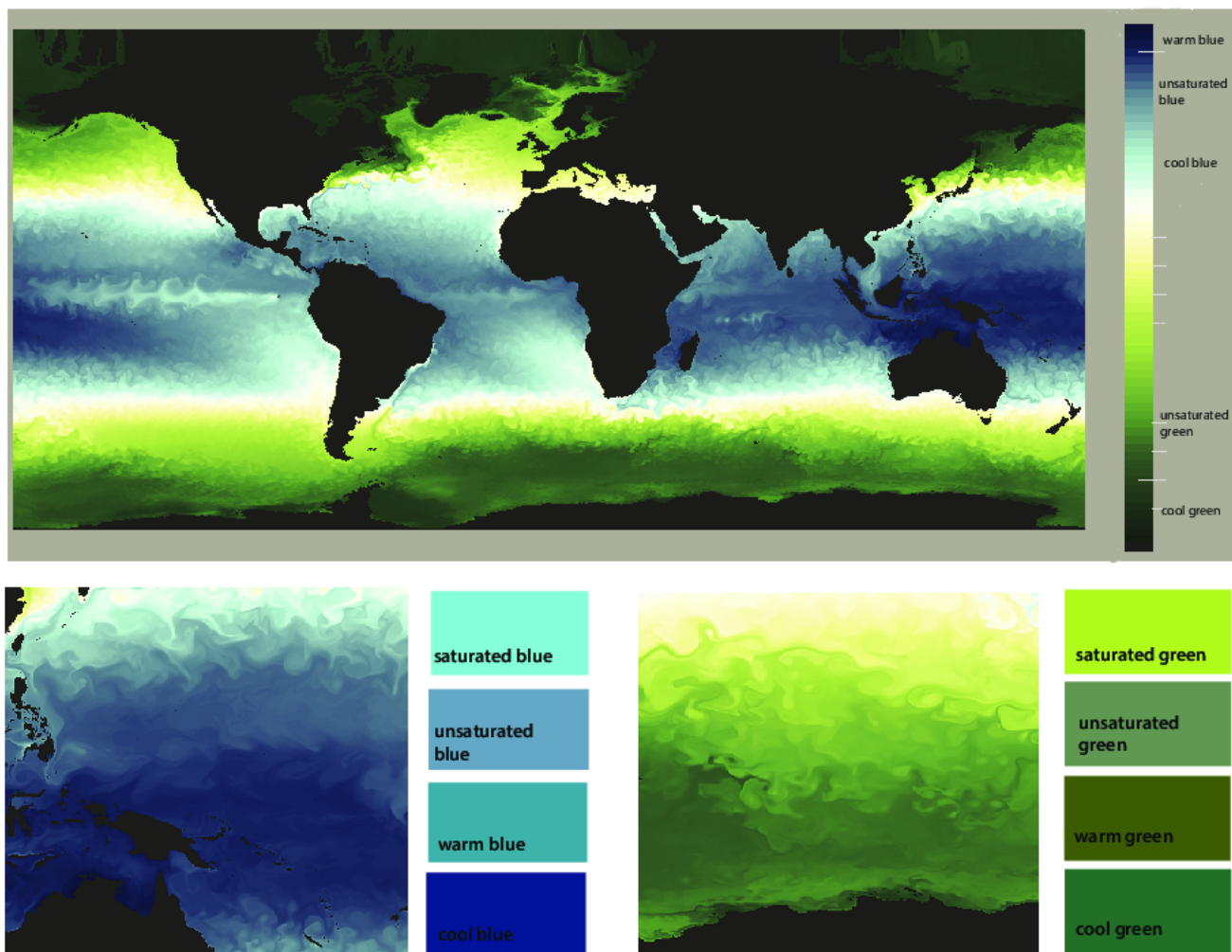


Figure 11: Above is an asymmetrical divergent color scale. The asymmetry allows you to easily change above which both hue ranges take advantage of the full range of each variable hue (within the blues and greens), saturation and value. The rectangles below illustrate the difference between warm and cool greens as well as saturated and unsaturated hues.

reduced alpha value enables us to focus attention on one specific section of a visualization, as shown in Figure 9. A semi-transparent plane of a cool color complement is shown intersecting with a plane of data. All of the data is still visible, but our attention is directed to the lower areas which are *not* covered by a screen of the heat map's complement, and are thus not muted.

### 3.5 The Impact of Contrast of Extension

Contrast of Extension, if not managed properly, has the potential to significantly distort our perception of area relationships within an image. As an example, we perceive harmony and balance when red and green appear in equal amounts. Yellow/purple complements need a 1:3 ratio to achieve similar harmony. Orange/blue needs a 1:2 ratio. This effect is most pronounced in fully saturated colors. [6]

In order to create visualizations in which the colored areas are perceived in the ratio of the actual area depicted, one must avoid fully saturated complements. If an image has predominant areas of saturated complements, our minds alter our perception of the size of an area to more closely match ideal ratios. In Figure 6, the upper section shows the ratio in which each set of complements is per-

ceived accurately, as depicted. The lower portion shows a red/green complement in balanced ratio on the left versus unbalanced on the right. In the image on the right, we perceive the red areas as larger than they actually are. Our minds are attempting to move the image toward a harmonious balance. Contrast of Simultaneity along with Contrast of Extension account for much of the perceptual distortion created by the rainbow color scale.

## 4 THE PATH TO USABILITY

As noted before, the workflow for creating these color scales requires a large number of control or color points (typically around 20), and this means they would tend to be unwieldy in practice when used with today's tools.

We explored ways to simplify the representation by using different types of functions for encoding hue, saturation, and value. Our process began with extensive interaction between an artist and a statistician to understand the different properties of curves that would be desirable for developing effective color scales. This led to the identification of several families of curves that could be used to represent the typically nonlinear gradations in the color components used by the artist. These different families of curves can be



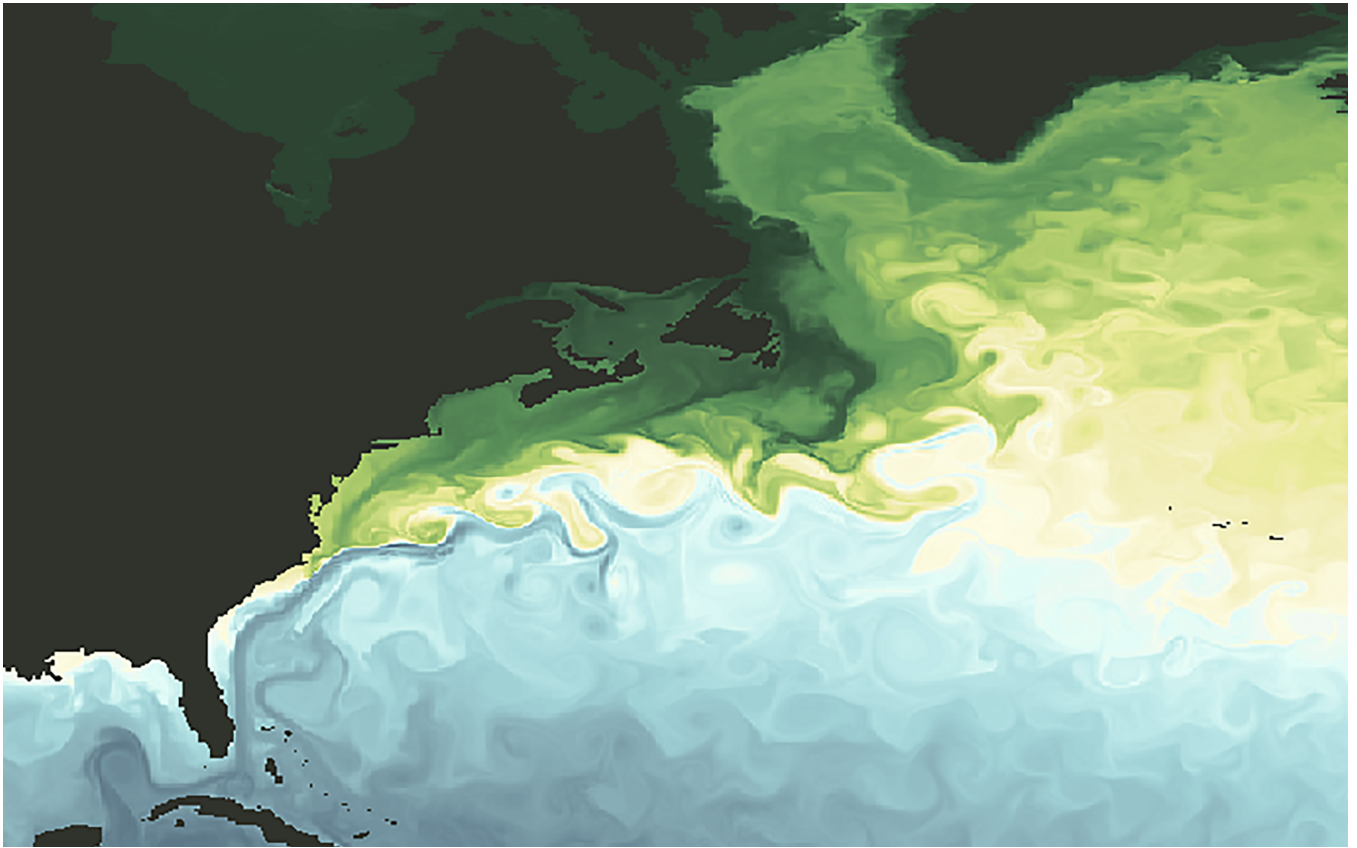


Figure 12: Low values on a divergent color scale create an unintended focal point as shown in the white areas above. To take advantage of this characteristic our color scales are constructed so that the divergent point of the color scale can be moved, thus refocusing the most perceptually variable section of the color scale on different sections of the data/vis. The color scales contain a large enough range of contrasting steps to retain perceptual differentiation with in the expand side of the color scale.

used to achieve different effects. **Note:** **B** shows two color scales, the top one created by the artist. The artist then selected specific H, S, and V values along the color scale. Those values were then plotted, as shown, and the statistician developed functions to simulate the curves. Fine-tuning the parameters can achieve the desired behavior in the resulting color scale.

The curves that were designed for H, S, and V make use of different functional forms of an index -  $x$  - defined on the interval  $[0,1]$ .

In this example, *Hue* is modeled using a logistic curve, *saturation* is modeled using a sine function, *value* is modeled using a reciprocal function of  $x$  squared.

$$H = \frac{\theta_1}{1 + \theta_2 \exp(-\theta_3 x)}$$

$$S = \theta_1 \sin(\pi x)$$

$$V = \theta_1 + \theta_2 \left( \frac{1}{1 + \theta_3 x^2} - \theta_4 \right)$$

Identification of appropriate mathematical functions facilitates implementation of an automated representation of the artistically generated color scales suitable for computer implementation. As discussed above, parametric functions provide a rich set of options for creating a variety of color scales. The H, S and V curves follow similar patterns across varying color scales. Thus a minimal number of functions can be used to create a range of color scales.

Various types of nonlinear functions used in growth curve modeling [4] provide nonlinear curves with parameters that can be tuned to achieve a variety of shapes. If the artist has an existing color scale represented by a set of distinct points that exhibits reasonably smooth underlying behavior (e.g. with continuous first derivative behavior), polynomial approximations can be automatically constructed that will capture the essence of the artist's color scale. Figure 13 shows graphs from two different color scales, illustrating this collaboration. On the left is a set of HSV curves generated from mathematical functions designed to capture the artist's HSV values across the color scale. On the right is a set of HSV curves for a different color scale, showing curves generated from polynomial fits to a color scale provided by the artist.

Working together, the artist and the statistician are able to meld the perceptual and design considerations with the algorithmic needs of the computer scientists to generate digital representations. The reason for developing analytical representations is not simply to mimic existing artistically generated maps, but to stimulate rapid creation of color scales that capture different types of perceptual effects by enabling rapid review of a wider range of effective options. Ultimately, the goal is to produce color scales for scientific visualization that support further exploration of visual perception and effective information transfer.

## 5 CONCLUSION

Should scientists worry about color? Rogowitz [11] and others believe it's important, and we agree.

We can see in visualizations such as Figure 3 that manipulating

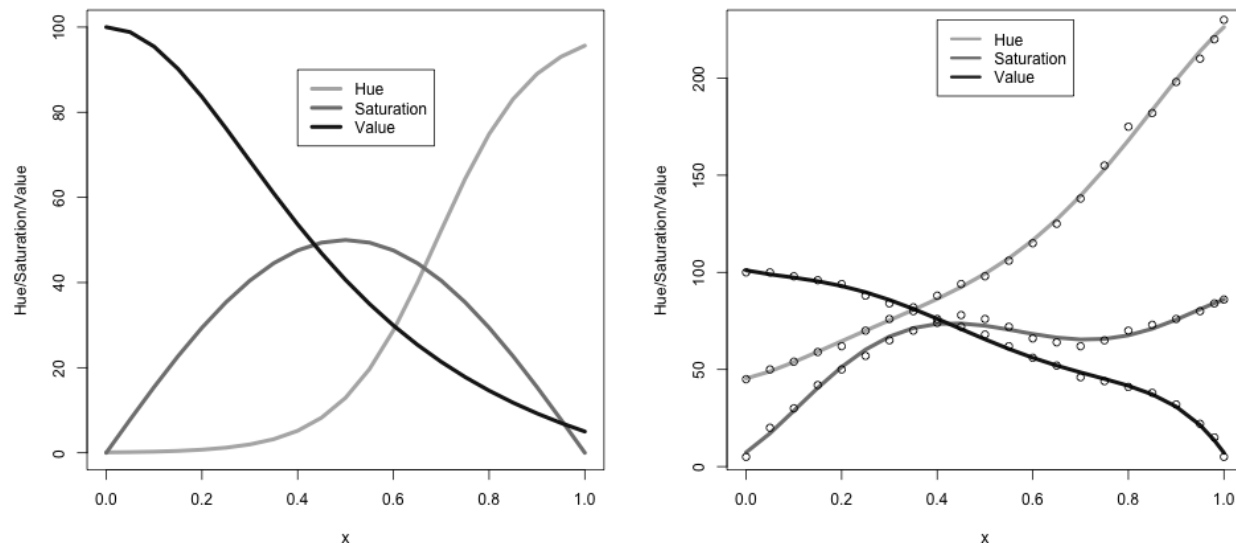


Figure 13: HSV curves from two different color scales, showing the collaborative development of smooth curves by an artist and a statistician. On the left, curves for H, S and V that have been mathematically modeled by the equations shown in the text to achieve hue, saturation and value patterns modeled by the artist. On the right, HSV curves represented by a set of points from an artist's initial color scale along with a set of polynomial fits to the variables that capture and smooth the behavior of the original color scale and provide an analytical representation for the computer generation of points for the color scale.

Itten's color contrasts can increase the detail shown in visualizations, even using a commonly utilized color scale. Visualizations such as Figure 12, Figure 7, and Figure 10 demonstrate that careful selection of colors can show a wide range of distinguishable sections within continuous data, even when a small set of hues is utilized.

A color scale that creates a harmonious visualization not only equalizes our attention, it create a quiet image allowing room for a larger number of non-distracting variables. Our team includes an artist not to simply make a pleasing visualization, but to intentionally remove interactions of color from our visualizations, creating a harmonious balance which allows researchers to perceive data accurately. The goal is contrast without cacophony.

Harmony is an equalizer. It balances all the elements within an image. Artists seek harmony within their work so that it is engaging, and can be fully absorbed and appreciated without distraction. Through the examples in this paper, we have demonstrated that application of artistic color concepts to visualization can have an analogous effect.

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